# Implementation of WAVEWATCH III at Fleet Numerical Meteorology and Oceanography Center

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**Abstract - Fleet Numerical Meteorology and Oceanography Center (FNMOC) is in the process of transitioning its operational models suite from a Cray C90 shared memory architecture to SGI Origin 2000 (O2K) and Origin 3000 (O3K) distributed memory systems. As part of this transition, the third generation WAVEWATCH III (WW3) wave model is currently being implemented to replace the third generation Wave Model (WAM). WW3 offers several advantages over WAM. For example, WW3 has a third-order accurate wave propagation scheme that reduces the numerical diffusion of swell energy characteristic of the first-order scheme used in WAM. Also, WW3 has been programmed to run efficiently on distributed memory computers. The global implementation of WW3 was ported to the O2K in December 2000, with atmospheric forcing provided by the FNMOC Navy Operational Global Atmospheric Prediction System (NOGAPS) model. Regional versions of WW3 have also been implemented on the O3K computer in six areas of naval interest. The wave models were run in parallel two months and the results are compared to wave height measurements. WW3 became operational at FNMOC, replacing WAM, in August of 2001.**

## I. INTRODUCTION

Fleet Numerical Meteorology and Oceanography Center (FNMOC) has pioneered the use of spectral ocean wave models for operational use, beginning with the implementation of the Spectral Ocean Wave Model (SOWM) for the Mediterranean Sea in 1972 [1]. The SOWM was expanded to cover the Northern Hemisphere in 1975 [2], and a global version (GSOWM) was implemented during 1985 [3]. The third-generation wave model WAM was developed in the late 1980's [4] and adopted for operations at FNMOC in 1990 to replace the Mediterranean SOWM [5]. With the acquisition of the Cray C90 supercomputer in 1994, WAM was implemented globally on a 1-degree latitude/longitude grid, replacing GSOWM [6]. Since this time, many high-resolution regional WAM implementations have been nested within the global WAM. The development and implementation of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) at FNMOC has provided the opportunity to run high-resolution regional WAM models forced by mesoscale winds [7].

WAM has been adopted by other weather forecasting centers around the globe for operational use. These include the National Centers for Environmental Prediction (NCEP), United Kingdom Meteorological Office (UKMO), Canada's Atmospheric Environmental Service (AES), Australia's National Meteorology Operations Center (NMOC), the European Centre for Medium-Range Weather Forecasts (ECMWF), and the U.S. Naval Oceanographic Office (NAVOCEANO). A comparison of wave predictions from the various centers was performed on a monthly basis [8]. As centers gained operational experience with WAM, certain model tendencies were noted [9]. These included under prediction of peak wave events and the under forecasting of swell events [10]. In the fall of 1999, NCEP replaced WAM with WW3 [11].

WAVEWATCH III (WW3) is a third-generation wave model developed at NOAA/NCEP to address the error tendencies known to exist in WAM [12]. It employs a third-order numerical propagation scheme in order to control numerical diffusion of swell. Although the wave growth and dissipation source terms are also different than those of WAM, both wave models exhibit similar wave growth characteristics.

WW3 uses approximately 40 megawords of memory on the Cray C90 for the global implementation and 1260 CPU seconds/24 hour integration, while WAM uses 70 megawords and 960 CPU seconds/24 hour integration. Thus, in general comparison, WW3 uses about 40% less memory but about 30% more CPU time than WAM. WW3 is coded to take advantage of distributed memory computers using Message Passing Interface (MPI) subroutine calls.

## II. PARALLEL RUNS

WW3 and WAM were run in parallel on the FNMOC Cray C90 computer during January and February, 2000. Both models were run on a global 1° latitude by 1° longitude grid, with the identical land mask used for the operational WAM. WW3 was forced by NOGAPS 10m height winds, while the operational WAM was forced by NOGAPS surface wind stress. From previous comparison it was found that the impact of using the surface winds instead of the wind stress to force WAM is negligible. The wind time step was three hours for both models. The models were run on a 6 hourly update cycle using the forecast wave spectra as the initial condition for the next run. Both models used the same ice analysis to update the ice edge. The operational WAM ran in deep water mode (i.e., there was no dissipation due to bottom friction). WW3 used bottom friction to dissipate wave energy where the bottom depth influences the waves. Significant wave height, peak wave period, and wind speed were archived for both WW3 and WAM.

WW3 and WAM were verified using National Data Buoy Center (NDBC) wave buoys and ERS-2 altimeter wave height measurements. The significant wave height and peak wave period from the wave models were interpolated to the wave measurement locations. Then standard statistics, such as bias, root-mean-square error, scatter index, etc., were computed. The error statistics were computed on both a global and regional basis.

## III. ERS-2 COMPARISON RESULTS

The ERS-2 altimetry wave height data were collected and processed during the test time period. The data were checked for gross errors and decimated using a 9 point medium filter. A correction was applied at the high wave height range [11]. This correction, based on comparisons to buoys, increases the wave height measurement in the upper wave height range. The ERS-2 altimeter does not measure wave heights below 0.5 m and no attempt was made to correct the wave heights in this range. The model nowcasts were interpolated to the ERS-2 data locations using a 6 hour time window centered on the 00, 06, 12, and 18 UTC synoptic times. Figures 1 and 2 are scatter plots of the ERS-2 altimeter wave height measurements compared to WAM and WW3 model nowcasts, respectively.

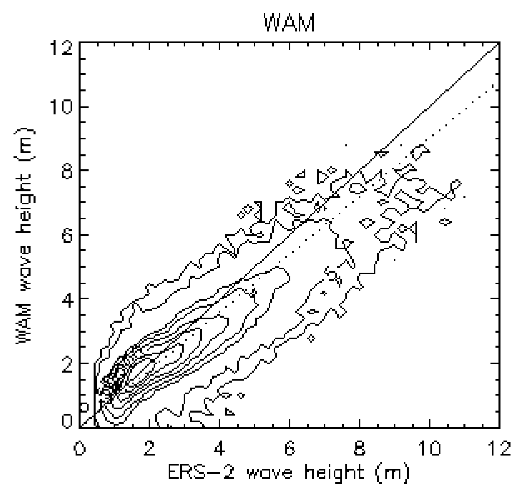


Fig 1. WAM/ERS-2 Wave Height comparison for Jan 2000. Bias=-0.22m; RMSE=0.63m; Scatter=0.22; Obs.=71942

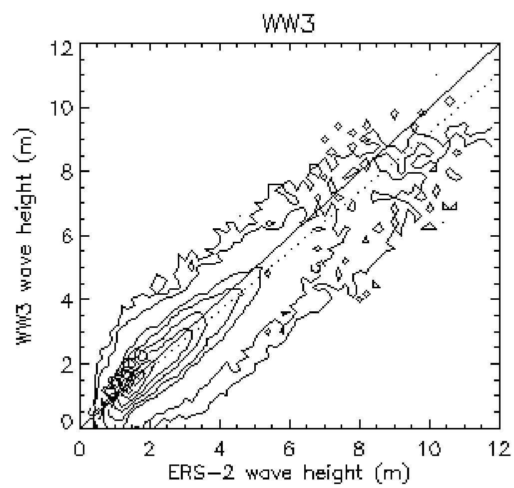


Fig. 2. WW3/ERS-2 Wave Height comparison for Jan 2000. Bias=-0.20m; RMSE=0.58m; Scatter=0.19; Obs.=71942

The point density has been contoured and the error statistics are given below the figures. For all months, WW3 has a slightly smaller RSM error and scatter index than WAM. This is mainly due to the better agreement of wave heights in the high (6 to 10 m) range. Differences in the model biases are statistically significant at the 95% level. Although these comparisons were made for July 1999 through February 2000, only the results for January 2000 are shown here. Results from the other months are similar.

To look at regional differences in the ERS-2 error statistics, the measurements for January and February were grouped into seven regions. These regions are the North Pacific (NP; north of 20N latitude), the Equatorial Pacific (EP; latitudes 20S to 20N), the South Pacific (SP; south of 20S latitude), the North Atlantic (NA; north of 20N latitude), the Equatorial Atlantic (EA; latitudes 20S to 20N), the South Atlantic (SA; south of 20S latitude) and the Indian Ocean (IO). Results are presented in Table I. Although WAM had a smaller bias in most regions, WW3 has a smaller RMS wave height error, in most regions.

TABLE I
Regional Error Statistics

| | Obs | Bias(m) | | RMSE(m) | |
|---|---|---|---|---|---|
| | | WAM | WW3 | WAM | WW3 |
| NP | 21519 | -.32 | -.26 | .80 | .74 |
| EP | 26612 | +.07 | -.20 | .43 | .44 |
| SP | 30071 | -.28 | -.34 | .72 | .65 |
| NA | 18604 | -.36 | -.34 | .76 | .75 |
| EA | 10368 | -.15 | -.29 | .42 | .43 |
| SA | 15937 | -.14 | -.14 | .58 | .59 |
| IO | 33374 | -.41 | -.28 | .68 | .59 |

## IV. BUOY COMPARISON RESULTS

Predictions from both WW3 and WAM were compared with observations from a set of 48 buoys, located in the northern hemisphere, mainly in the North American coastal areas and near Hawaii. The results of all the buoy comparisons are shown in Figures 3 and 4, for WAM and WW3 respectively. The bias and RMS error for WAM is slightly less than that of WW3 for the nowcast. However the correlation coefficients are the same for both models. Table II shows buoy error statistics as a function of forecast time. Wave height errors normally increase with forecast time due to

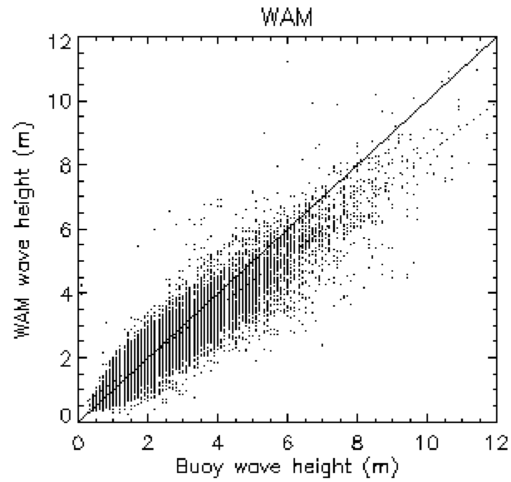


Fig. 3. WAM/buoy wave height comparison, Jan-Feb, 2000. Bias=-0.16, RMSE=.65m, CC=0.92

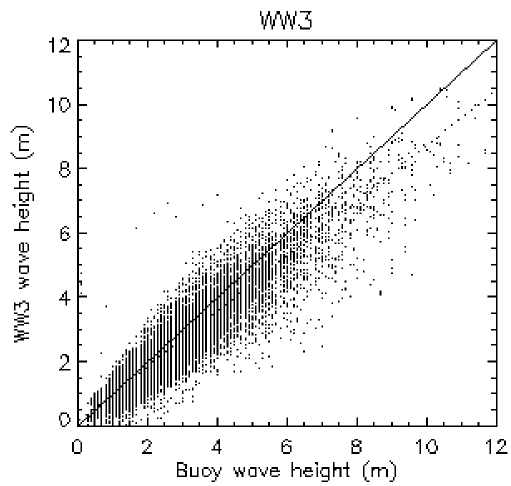


Fig. 4. WW3/buoy wave height comparison, Jan-Feb, 2000. Bias=-0.26, RMSE=0.67m, CC=0.92

TABLE II
Error Statistics verses Forecast Time

| Fcst. Time | WAM | | WW3 | |
|---|---|---|---|---|
| | RMSE | CC | RMS | CC |
| 00 | 0.65 | 0.92 | 0.67 | 0.92 |
| 24 | 0.71 | 0.90 | 0.73 | 0.91 |
| 48 | 0.79 | 0.87 | 0.81 | 0.88 |
| 72 | 0.81 | 0.82 | 0.83 | 0.83 |

increasing forecast errors in the surface winds. WAM maintains a smaller bias and RMSE through the 72-hour forecast. However, the correlation coefficients are approximately the same.

It is also useful to look at individual time series of buoy observations and model nowcasts.

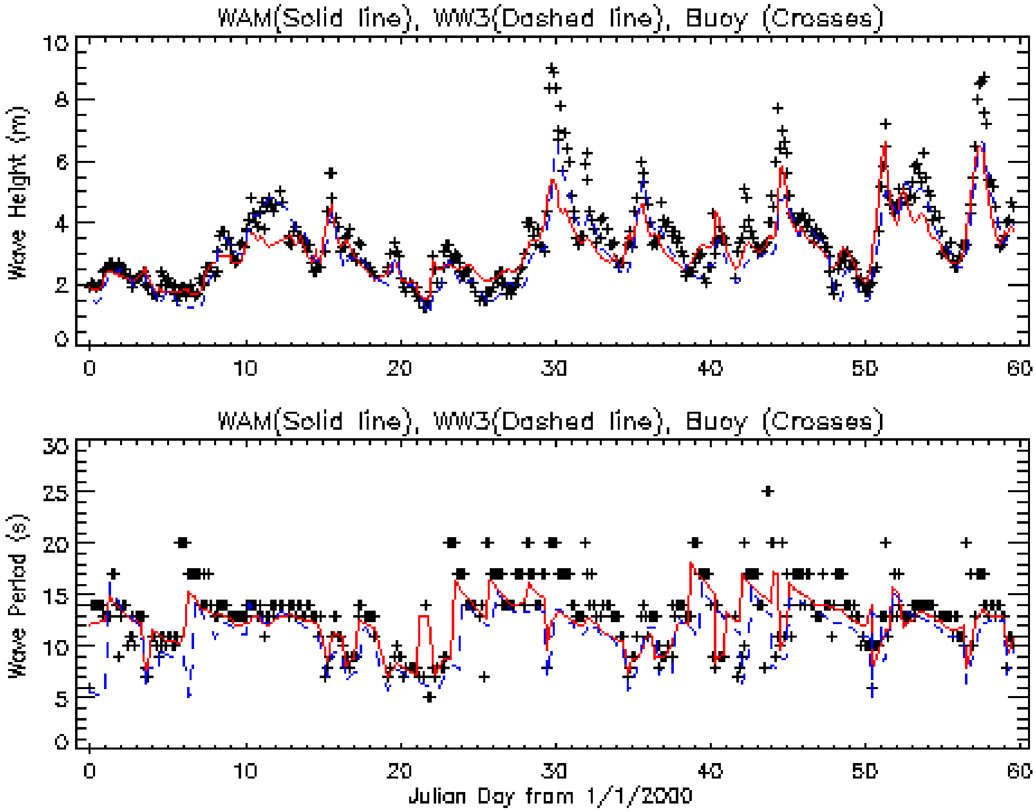


Fig. 5 Time series of wave height and period from buoy 46059.

Figure 5 shows the wave height and wave period from buoy 46059, located in deep water, about 300 miles west of California. Also plotted are the wave model estimates from WAM and WW3. Although both models track the observations well, WW3 can be seen to better follow the wave height range, while WAM is somewhat unresponsive and biased high. If we look at peak wave events on day 30, WW3 come closer to the measured maximum wave height. From the peak period time series we can see the signature of swell arrivals and decay as a rapid rise in the peak period followed by a gradual reduction. Both models underestimate the maximum periods (greater than 20 seconds) at the onset of swell events. This behavior is common to most numerical wave models. WAM seems to better time the arrival of the swell events.

Although not shown here, buoy time series from different regions were examined to study the tendencies of the wave models in different geographic regions. These regional buoy statistics are summarized in Table IV. As with the ERS-2 comparisons, the results from the regional buoy statistic are mixed. If one compares the RMSE, WAM performs better in most areas. One area were WW3 clearly demonstrated better performance was Hawaii. The results from the Hawaiian buoys were consistent with the results from the ERS-2 comparisons, in the equatorial Pacific. Here WW3 had a smaller bias and RSME.

## V. DISCUSSION

Overall, WAM had smaller RMSE compared to the buoys, however at two buoy clusters, Hawaii and U.K., WW3 had a smaller RMSE. These results are consistent with those of Tolman [11], who compared the NCEP 1.25 x 1.00 degree resolution WW3 to the 2.5 x 2.5 degree resolution NCEP operational WAM. This study compares WAM and WW3 running on the same 1.0x1.0 degree grid.

Looking at individual wave events in the buoy time series, there are cases were WAM comes closer to the wave height maximum, while in other cases WW3 comes closer. WW3 lags WAM and the observations for swell arrivals at some of the California coastal buoys. WW3 also tends to have a time lag during increasing wave height events. The ERS-2 measurements cover the global oceans while the buoys are confined to coastal areas in the northern hemisphere.

Verification results based on the buoy data varied regionally and tended to favor WW3 over WAM in swell-dominated regions. However, the overall results derived from all of the buoy data showed no significant difference in skill between the two models. The ERS-2 data, which provided about 10 times as many observations and much broader spatial coverage than the buoy data, favored WW3 over WAM in most statistics.

Table III
Regional Buoy Significant Wave Height Statistics
For January and February, 2000.

| Region | No. Obs | Bias (m) | | RMSE (m) | | Cor. Coef. | |
|---|---|---|---|---|---|---|---|
| | | WAM | WW3 | WAM | WW3 | WAM | WW3 |
| West Coast | 3452 | -.25 | -.44 | .70 | .73 | .84 | .86 |
| Hawaii | 2000 | .08 | -.09 | .43 | .36 | .71 | .83 |
| Pacific NW | 3258 | -.14 | -.28 | .68 | .69 | .90 | .90 |
| NE US Coast | 3535 | -.13 | -.30 | .58 | .69 | .92 | .90 |
| Gulf of Mexico | 1731 | -.18 | -.15 | .44 | .45 | .84 | .80 |
| SE US Coast | 431 | -.26 | -.40 | .46 | .52 | .90 | .92 |
| Japan | 879 | -.05 | -.16 | .46 | .53 | .88 | .85 |
| UK | 2739 | -.38 | -.24 | .82 | .79 | .94 | .93 |
| Gulf of Alaska | 1584 | .08 | -.06 | .75 | .73 | .88 | .88 |

## VI. SUMMARY

FNMOC will replace WAM with WW3 as the operational forecast model in August 2001. From buoy and satellite derived date comparisons, WW3 preformed as well or better than WAM during the operational test period. WW3 also runs efficiently on the SGI Origin 3000 distributed memory systems, which are replacing the Cray C90 shared-memory vector machines at FNMOC.


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